DIRECT STEAM GENERATION USING THE SG4 500m^2 PARABOLOIDAL DISH CONCENTRATOR

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Abstract

The ANU 500 m^2 dish is the first prototype of a new design geared towards mass production and low levelised cost of energy. The dish has high quality optics, with a geometric concentration ratio above 2200, and can be used for a variety of energy conversion technologies. The SG4 concentrator is currently being operated in direct steam generation mode with a monotube steam receiver. Experimental runs have been carried out at the receiver design conditions of 500 °C and 4.5 MPa, as well as at lower temperatures and pressures, for periods of up to 8 h of continuous operation. Results to date yield receiver conversion efficiencies over 90% during quasi steady-state periods. Convection losses are predicted to increase with decreasing dish inclination, but the effect on the receiver efficiency is small due to the high concentration ratio. Receiver temperature profiles correlate well with predictions from optical modeling. Work is continuing on refining the experimental methodology and collecting on-sun data.

Keywords: Solar, dish, steam, cavity, receiver, convection.

1. Introduction

The SG4 500m^2 dish system (Figure 1) was completed on the ANU campus in 2009 and initial results on its optical performance were reported at the SolarPACES conference in that year and subsequently in [1]. The design and construction of the system follows on from earlier ANU big dish designs implemented in Canberra and for the Ben Gurion University in Israel. Very high concentration levels have been achieved, with a peak of 14,100 suns and a geometric concentration ratio of 2240 for 95% capture.

Parameter	Value
Mirror aperture area	489 m^2
Focal length	13.4 m
Average diameter	25 m
Average rim angle	50.1°
Mirror reflectance	93.5%
Number of mirrors	380
Mirror size	1165 x 1165 mm
Total mass of dish	19.1 t
Total mass of base and supports	7.3 t

Table 1. SG4 dish specifications

The design brief was for a large-area solar dish which produces energy at minimum levelised cost when mass produced for large scale arrays. The system developed uses a full sized convex jig on which the dish front surface members and space frame are assembled. The jig has multiple adjustable support points, which were adjusted to an RMS deviation of ±0.6 mm from the true paraboloid. The mirror panels are glued to the completed dish frame without any alignment adjustment. All mirror panels are approximately spherical “best fit” curvature. Dishes can be constructed using panels with identical radius of curvature (R.O.C.); or, if greater accuracy is desired, panels with two or more R.O.C. classes, installed in different sections of the paraboloid, as was done with the JPL Test-bed Concentrator [2]. The laminated mirror panel construction produces units which also contribute structurally to the dish, thereby reducing cost.

The dish design is intended for deployment of large arrays rather than one or two units at a site. In a full scale direct steam generation (DSG) plant an array of dishes would direct steam to a central large steam turbine power block. As well as DSG, the ANU group is investigating energy conversion options involving ammonia dissociation, receiver mounted Brayton cycle engines, and hydrocarbon gasification using supercritical steam.

Fig. 1. An early test involving venting of steam from the SG4 receiver. Later tests have conveyed the steam to our 50 kWe steam turbine; the new dish is oversized for the current engine, so some venting is still required.

This paper addresses the direct steam generation activities. Experimental runs have been carried out at the receiver design conditions of 500 °C and 4.5 MPa, as well as at lower temperatures and pressures. Results to date indicate receiver thermal efficiencies in excess of 90% during quasi steady state periods. On-sun experiments are also being used as an input to modelling of two-phase flow within the receiver tubes and automation of temperature and mass-flow control [3][4].

2. Equipment

2.1. Steam receiver and steam engine

The SG4 dish is currently being operated with the direct steam generation receiver that was previously used on the older 400 m^2 SG3 dish. The higher concentration ratio of the new dish has allowed the same receiver to be used despite the larger size of SG4. The steam cavity receiver consists of a winding of steel tube coiled to form a cavity with an approximately top hat shaped cross section (Figure 2). Feed water enters the receiver at the beginning of a conical front section and exits at the top of the cavity; the conical section serves to collect spillage outside of the cavity entrance. The steel tube is comprised of approximately 110 m of 16 mm OD mild steel in the conical section and the start of the cavity, and 95 m of ¾ inch stainless steel in the remainder of the cavity. The tubes forming the cavity are covered with 200 mm thickness mineral wool insulation and enclosed with sheet steel.

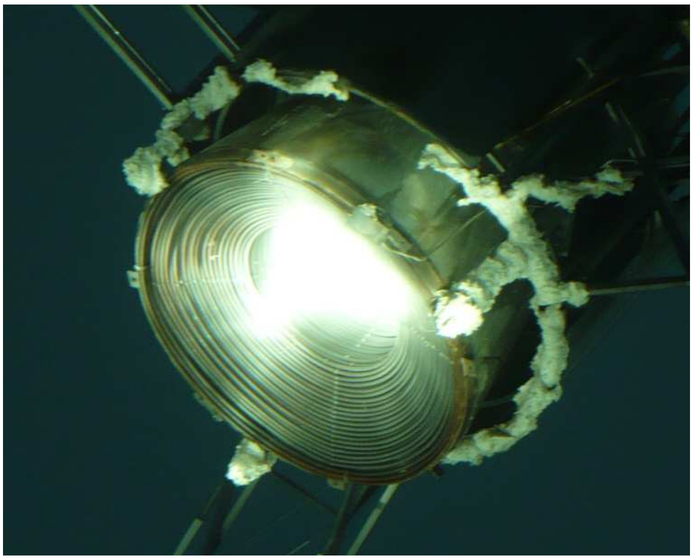

Fig. 2. Steam receiver on sun. White material is loosely-bound insulation to protect support frame.

High-temperature steam is brought back to the ground via rotary joints, then transferred to a four-cylinder steam engine and coupled three-phase generator. Electricity produced by the system was first put into the local electrical grid in February 2011. The generator set has a design capacity of 50 kW_e, which was adequate for SG3, but is insufficient for the full steam load from SG4. As a consequence, a variable fraction of the steam is vented just after the receiver, as shown in Figure 1, although, in practice, the amounted of steam released is much smaller. The vent valve gives some control over the backpressure seen by the receiver; work is at present being conducted into using the valve for automated backpressure regulation [4].

2.2. Instrumentation

Wind speed is measured by a pair of cup anemometers (Monitor Instruments Model AN2). One is mounted 5.5 m from ground level in a location 30 m from the centre of the dish, and was installed to measure ambient wind speed and (using an adjacent wind vane) direction. The other anemometer is mounted behind the dish receiver, with its rotational axis parallel to the axis of the dish. It thus primarily responds to the component of the wind parallel to the aperture plane of the receiver (see Section 4.1.). The ground mounted anemometer has proven to be a poor indicator of the actual wind speed experienced by the dish, based on comparison with readings from the receiver anemometer when the dish is in the park position. The immediate surroundings of the dish are quite built up, with nearby trees, buildings, and hills, and the response of the anemometer is significantly dependent on the wind direction.

Type 'K' Thermocouples are located throughout the receiver tube windings and give the temperature profile through the receiver. The majority of the thermocouples are welded to the outside of the tubes, on the insulated side, and thus measure the tube wall temperature; a smaller number are inline in stainless steel sheaths.

Pressure transducers (Yokogawa EJX510A) are located at the receiver inlet and outlet, as well as at other points in the system. An Eppley Normal Incidence Pyrheliometer (NIP) is used to measure direct beam insolation.

Instrumentation is connected to a Yokogawa FAM3 programmable logic controller (PLC, also used for controlling the dish), HXS10 Solar Tracker, and MW100 data logger. Yokogawa Fasttools SCADA software connects to all units and is used for global data logging, generally with logging interval of 2 seconds.

The reflectance of the dish is measured using a laser reflectometer built in-house at ANU. The detector is masked so as to give an acceptance angle equivalent to that of the dish receiver, in order to reject light which is scattered by dust particles and which would not be incident on the receiver [5][6]. Reflectance measurement is discussed in detail in Section 3.2.1.

3. Experimental results

Since the commissioning of the steam engine system there have been approximately 25 days of on-sun runs, ranging from late-summer to mid-winter, with duration up to 8 hours.

3.1. Receiver temperature profile

The temperature profile through the receiver in steady-state and transient conditions is being used in the development and validation of a model of two-phase flow in the receiver [3]. Boiling is found to always occur in the region of highest flux within the cavity (~600 to 1000 mm from the front of the cavity), rather than in the front conical section of the receiver. Figure 3 shows on the same graph a typical temperature profile during steady state operation and the predicted cumulative flux on the receiver.

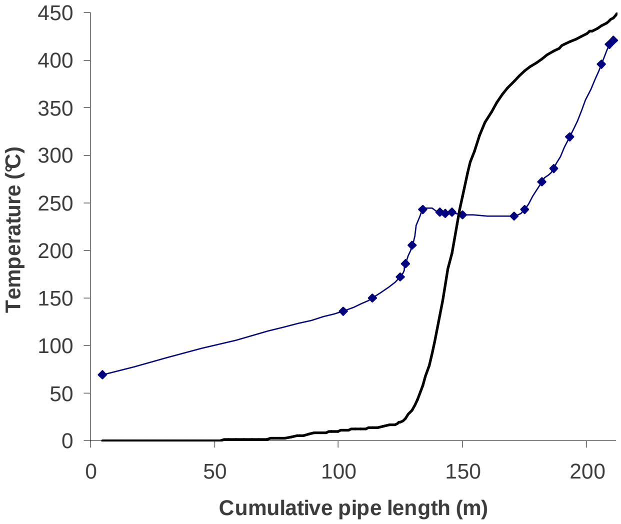

Fig. 3. Measured temperature profile at the tube external thermocouples (blue curve with data points) and cumulative flux incident on the receiver derived from Opticad modelling (solid line, y axis normalised such that full scale represents the total incident flux).

Figure 3 shows that the temperature change of liquid water and superheated steam are linked to the local incident flux per length of pipe where the change is experienced. In the first 120 m of pipe, the change in temperature is slight, due to the low amount of cumulative flux. Around the 125 m mark, liquid water temperature changes to coincide with the sharp increase in flux per length. Superheated steam occurs around the 170 m mark and the temperature increases per length are consistent with a relatively even distribution of the remaining incident flux.

In the saturation region, the slight decrease in temperature along the pipe, up until approximately the 170 m position can be explained by the pressure drop experienced by the fluid as it travels along the 3/4 inch helically-coiled pipe while still in saturation and gaining more energy. The temperature drop yields information about the pressure inside the pipe during saturation and the pressure drop per length of this boiling process. The boiling region coincides with the region of highest incident heat flux, as can be expected; this helps to confirm earlier ray-tracing results.

3.2. Receiver efficiency

The energy conversion efficiency of the steam receiver η_{rec} is here defined as:

$$\eta_{rec} = \frac{\dot{m}\left(h_{\mathrm{rec,\,out}} - h_{\mathrm{rec,\,in}}\right)}{q_{\mathrm{rec}}} \qquad (1)$$

where $\dot{m}$ is the mass flow rate, $h_{rec,out}$ is the enthalpy of the steam out of the receiver, $h_{rec,in}$ is the enthalpy of the feedwater entering the receiver, and q_{rec} is the power of the radiation incident on the receiver. Enthalpy values are calculated on the basis of measured temperatures and pressures, which requires sub-cooled or superheated states at both inlet and outlet. q_{rec} is calculated from the measured insolation and dish reflectance:

$$q_{rec} = \gamma \rho A G \tag{2}$$

where γ is the intercept (capture) fraction for the receiver, ρ is the average mirror reflectance, G is the direct normal irradiance (DNI) and A is the un-shaded mirror aperture area of 484 m^2. Based on lunar flux mapping [1], more than 99% of the reflected radiation is intercepted by the cavity or the outer cone of the receiver, and so γ is set to 1.

Receiver efficiencies should ideally be determined at steady state operating conditions. In an experimental study on central tower receiver [7], 'steady state' conditions were defined as a period of at least 30 minutes in which all relevant parameters (insolation, outlet temperature, mass flow rate etc) have only small variations from their mean values during this period[1]. Such conditions have seldom been attained in dish runs to date. Steam temperature control is currently implemented by manual adjustment of the mass flow rate, and even small changes in ambient conditions (such as wind speed and direction and insolation) can result in unstable receiver outlet temperatures. Efficiencies were instead calculated for quasi steady-state operation periods, defined as at least 5 minutes of operation with small variation, and no major changes in relevant parameters immediately prior to the period. Measured efficiencies are shown in Figure 4, and are in all cases greater than 90%. The data set is relatively small, as on many occasions steady-state was not achieved, either due to ambient conditions or to intentional changes in parameters such as mass flow rate and back pressure. Some dates also lacked good dish reflectance data and are not included. The high values of efficiency for 3-4 March also appear to poor accuracy in measurements, again probably from reflectance measurement, or some other calibration issue.

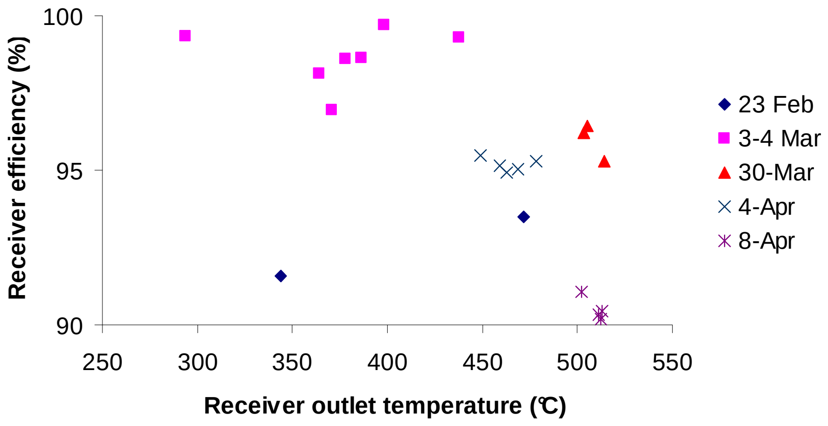

Fig. 4. Receiver efficiency versus outlet temperature during quasi steady-state conditions. High calculated efficiencies for 3-4 Mar are attributes to low-accuracy mirror reflectance data.

A trend of increasing receiver efficiency with decreasing operating temperature is expected due to reducing heat losses. However due to the uncertainty in the reflectance measurement (see below) it is not possible to define a parametric relationship until a larger data set is obtained, preferably from runs made when the dish has less variation in reflectance.

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[1] The limits imposed in [7] are ±3% for mass flow rate and inlet temperature, ±2% for power values, and ±1% for other parameters.

3.2.1 Accuracy of receiver efficiency calculations

The majority of the experimental parameters which are used to calculate the receiver efficiency can be measured with good accuracy, the exception being the dish reflectance. A statistical study of heliostat field reflectance [8], during a period of one month without cleaning, found that there was no significant variation in mirror facet mean reflectances and that reflectance values were normally distributed. In contrast, there can be substantial variation in mirror cleanliness across the dish surface, which increases the uncertainty in average dish reflectance. Until recently dish cleaning was manual and carried out relatively infrequently (a prototype automated dish cleaning device is now in operation), and dust and other soiling (e.g. from bird droppings) accumulate quite inhomogeneously across the dish. The mirror surfaces near the dish rim are generally cleanest, in part because rain is more effective in washing away dirt from these areas with greater slope.

A thorough study of the SG4 dish reflectance was made on one occasion, with 280 measurements made in the dirtiest region of the dish, which exhibit the greatest amount of variation, and a smaller number elsewhere. A statistical analysis of the distribution of reflectance values was used to determine a protocol for reflectance measurement which balanced the time against the desired level of accuracy. It was found that making 20 randomly-located measurements in each of the three distinct regions of dish cleanliness gives a 95% confidence bound of -1% / +4% (the bounds are unequal as the distribution of reflectance is quite skewed; bounds decrease when the dish is cleaner as there is then less variation). This statistical measurement error is additional to the intrinsic error and repeatability of the reflectometer, the latter being approximately ±1% when measuring a clean surface.

It is possible that the monochromatic wavelength used by the reflectometer does not give a reliable estimate of the solar spectrum weighted reflectance; a study on the wavelength dependence of dust scattering found little variation [6], but this is still noted as a possible source of error.

Another factor of interest is the pyrheliometer accuracy, both in respect of its calibration and repeatability. A detailed investigation of the accuracy of a number of radiometers and pyrheliometers found that Eppley NIP units could have up to ±1% variation from their mean calibration, with an apparent correlation with solar zenith angle [9].

4. Discussion

4.1. Receiver efficiency and convection losses

In a computational fluid dynamics (CFD) study on natural convection from solar cavity receivers it was found that these losses are approximately linear with dish inclination [10]. For the steam receiver currently in use on SG4, at a receiver wall temperature of 450 °C, the line of best fit to the CFD data points has a slope of 0.135 kW per degree of inclination[2]. Based on the CFD model (which agrees reasonably well with a number of other studies), an inclination angle decrease of 30°, for example, produces an increase in the natural convection loss of only 4 kW. This represents only 1% of the incident energy; as the reflectance and insolation cannot be measured to this level of accuracy, and there is also the influence of forced convection, it is not possible to reliably determine the inclination dependence of the receiver efficiency using data collected at different dates. In an experimental study of dish based ammonia dissociation system at ANU the receiver efficiency was found to have significant dependence on inclination [11]. However the dish used in the ammonia experiments (which is 9 m^2 in effective area) had a geometric concentration ratio of only 300, which would result in much greater convective losses as a fraction of the incident energy, in comparison to SG4.

CFD modelling of forced convection losses from the current receiver was also carried out by Paitoonsurikan [12][13]. It was found that for a dish receiver forced convection is primarily driven by the component of the

[2] In reference [10] the receiver is referred to as "400m2" as it was originally installed on the SG3 dish of that size. The modelling does not incorporate the details of the flux distribution incident on the receiver, and is still applicable to the use of the receiver on SG4.

free stream wind velocity which is parallel to the aperture of the receiver. The “head-on” wind component has relatively little effect, in part due to shielding of the receiver by the dish at low inclinations. This conclusion was also reached in an experimental study [14], albeit for a receiver of a different geometry, under laboratory conditions. Forced convection due to the parallel wind component at moderate speeds (up to 3.5 m/s) produced inclination dependence comparable to that of free convection. However another experimental study (again under lab conditions rather than on-sun) of a similar design to the SG4 steam receiver found the converse result, i.e. that head-on wind produces larger forced convection losses [15]. The effect of shielding by the dish was not considered in [15], but this does not fully explain the discrepancy, and forced convection losses from dish receivers remains an area of ongoing research.

The SG4 dish is designed to track at wind speeds up to 11 m/s; however in practice at the ANU site the wind is usually quite gusty and a more conservative limit of around 5 m/s average wind speed is imposed. To date there is insufficient data to attempt to correlate receiver efficiency or convection losses with wind speed.

4.1.1. Convection losses and receiver design development

As discussed above, receiver convection losses are difficult to measure in on-sun operating conditions. An alternative approach is proposed for future receiver development, in which an experimental program will be conducted using laboratory-scale models. Convective losses from model receivers will be simulated in experiments that create buoyancy differences in a water-based model (by creating variations in salinity), an approach that offers the advantage of ready flow visualization and measurement. Further experiments using electrically-heated cavities to measure convective and radiative losses are also underway. Photogrammetry-based characterisation of the dish surface is being combined with ray-tracing to produce a more accurate flux distribution within the receiver cavity. This can be used to generate more realistic boundary conditions for CFD modeling than the assumption of uniform receiver wall temperature which was used by Paitoonsurikan [10].

5. Conclusion

The ANU SG4 dish is currently being operated in direct steam generation mode. On sun runs have been carried out with receiver temperatures up to 535 °C and 4.5 MPa, in runs lasting up to 8 h. Receiver efficiencies during quasi steady state periods are above 90%; however there is significant uncertainty in the calculation due to relatively poor accuracy in the dish reflectance measurement. Several steps are being taken to address this, including more frequent cleaning of the dish to reduce the reflectance variation across the dish and between runs, and further testing and calibration of the existing reflectometer.

Work is currently underway to develop automated steam temperature and backpressure regulation. On-sun experiments are also being used as an input to a model of two-phase flow in the receiver. Further lab-scale experiments are planned to allow improved prediction of heat loss for cavities of modified geometry.

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